Precision Farming: Challenges and Future Directions

Achim Dobermann[1], Simon Blackmore[2], Simon E. Cook[3], and Viacheslav I. Adamchuk[4]

[1] University of Nebraska, PO Box 830915, Lincoln, NE 68583-0915, USA, Email: adobermann2@unl.edu
[2] The Royal Veterinary and Agricultural University, Denmark, Email: simon.blackmore@kvl.dk
[3] CIAT, AA. 6713, Cali, Colombia, Email: s.cook@cgiar.org
[4] University of Nebraska, PO Box 830726, Lincoln, NE 68583-0726, USA, Email: vadamchuk2@unl.edu

Abstract

Precision farming is a systems approach to managing soils and crops to reduce decision uncertainty through better understanding and management of spatial and temporal variability. Much research has been conducted to develop strategies for site-specific crop management in different agricultural systems, with mixed results. Applications in which the sole focus has been on variable rate technology for managing spatial variation at the sub-field level have often failed to deliver significant and consistent improvements in crop yields, profitability, input use efficiency, and environmental impact. More robust, dynamic, and integrated forms of site-specific management are currently being developed. They require better techniques for characterizing and understanding crop growth determinants at the spatial and temporal scales that are most relevant for decision-making. This level of detailed understanding pays most in high-value crops, where more precise management can improve both quantity and quality.

Media summary

This paper reviews recent developments in precision farming and outlines directions for fine-tuning site-specific crop management to improve farm productivity, soil and environmental quality.

Key Words

Precision farming, site-specific crop management, variable rate technology, sensors, crop models

Precision farming as a systems approach to managing crops

Although precision farming (PF) started as a technology-led development, it is not just synonymous with yield mapping and variable rate technology (VRT) for managing spatial variability within a field. Instead, PF should be viewed as a systems approach to crop production in which the goal is to reduce decision uncertainty through better understanding and management of uncontrolled variation. Expertise from many disciplines is utilized, often also information technology, to bring data from multiple sources and scales to bear on decisions associated with crop production. If variability is the major source of uncertainty, it must be characterized and managed at the spatial and temporal scales that are most relevant.

The appropriate management processes and information needs vary among different environments, but also among different decisions to be made. For example, climate and crop yield potential primarily vary across larger regions and among cropping seasons. Variation in soil nutrient supply may be most significant within a large field, or among many small fields within a landscape. Both spatial and temporal variation must be characterized. Site-specific crop management (SSCM) then aims at improving the input - output characteristics of the soil and crop system as they vary in space and time. This may involve the use of advanced technologies at the sub-field scale, or simply by improving field-level inputs.

Practical steps usually include a cyclic process of: (i) characterization: measure extent, scales, and dynamics of variation, (ii) interpretation: assess significance, identify major causes of uncertainty, and formulate management targets, (iii) management: apply inputs at the appropriate scale and in a timely manner, and (iv) monitoring the outcome in a continuous learning process of change. This may be accomplished in discrete steps (“mapping approaches”), as dynamic processes executed in real-time (“sensing approaches”, “modelling approaches”), or as combinations of both. Crucial is the testing of the null hypothesis: given the large uncertainties evident in crop yield, is the outcome certain enough to justify significant change?

In Europe, environmental issues and poor public perception of agriculture have driven PF applications to focus on more efficient use of inputs. In North America and Australia, pressure to increase the profitability of agricultural production and, to some degree, environmental issues such as nitrate leaching or phosphorus runoff have driven PF research. In some developing countries, simplified forms of SSCM have been created, driven by the need to produce more food, utilize inputs more efficiently, and increase farm profits in response to declining food prices. General aspects of PF have been discussed elsewhere (Auernhammer 2001; Blackmore and Griepentrog 2002; Cook et al. 2003; National Research Council 1997; Pierce and Nowak 1999; Sylvester-Bradley et al. 1999). Here we wish to (i) examine selected recent developments by providing examples that illustrate the common theme of managing uncertainty caused by uncontrolled variation and (ii) evaluate future directions for PF research and adoption. Emphasis will be on issues that are mainly relevant for nutrient management in cereal systems.

Examples of site-specific management approaches

Nutrient management in maize-soybean systems in North America

The rainfed and irrigated systems of the U.S. Corn Belt are characterized by large fields and advanced technology used for growing crops such as maize and soybean. Despite significant increases in yields and nutrient use efficiency during the past 20 to 30 years (Dobermann and Cassman 2002), profit margins are small, a significant yield gap still exists, and agriculture’s contribution to contamination of ground and surface waters is cause for concern. Many PF technologies were initially developed in North America to increase profit, but the objectives have now changed to achieve sustainable profit while reducing environmental impacts associated with the use of agrochemicals.

In the past, PF in this region has focused much on using VRT to manage spatial variation within large fields, for example by variable rate application of N, P, K, lime or other inputs (Pierce and Nowak 1999). Initial research focused on studying spatial variation of soil attributes and crop yield, along with efforts on evaluating different sampling intensities for grid sampling and interpolation procedures for mapping (Franzen and Peck 1995; Wollenhaupt et al. 1997). Recognizing that high sampling cost represents a major obstacle to the profitability of PF approaches, emphasis later shifted towards utilizing a variety of data layers (e.g., maps of soil properties, terrain attributes, on-the-go sensed electrical conductivity, remote sensing, yield maps) to divide a field into few, larger sub-units commonly called “management zones” (Chang et al. 2003; Ferguson et al. 2003; Franzen et al. 2002; Ping and Dobermann 2003). Such zones or management areas are thought to behave differently in terms of soils and crop growth. They are used to direct soil sampling, identify location-specific response functions, and vary soil or crop treatments by zones.

Simulation studies have generally concluded that significant economic and environmental benefits could arise from variable-rate input application as compared to uniform field management (Batchelor et al. 2002; Bongiovanni and Lowenberg-DeBoer 2000; Wang et al. 2003). Requirements for this are that (i) significant spatial variation exists at the sub-field scale that can be measured accurately, (ii) crop response to inputs is significant, predictable, and not confounded by other factors, (iii) input applications can be done accurately, and (iv) the extra cost is kept low. So far, all of the above criteria have rarely been met when site-specific management strategies were implemented in the field. For example, although many field studies indicated that variable-rate N fertilizer application can reduce the N rate needed to achieve yields similar to those with common uniform management, increases in yield that would result in more significant increases in profitability have rarely been found (Table 1). It is also not yet clear whether VRT approaches can result in measurable decreases in nitrate leaching risk (Ferguson et al. 2002). Results have also been mixed for nutrients such as P and K or for liming (Bianchini and Mallarino 2002; Lowenberg-DeBoer and Aghib 1999; Pierce and Warncke 2000; Weisz et al. 2003; Wibawa et al. 1993). Variable rate application of these inputs generally increases soil test values in low-testing or acid field areas and saves inputs on high-testing areas, but such redistribution did not always increase crop yield or net returns (Swinton and Lowenberg-DeBoer 1998). It has been questioned whether applying existing fertilizer prescription algorithms to maps depicting spatial variation in soil attributes or crop yield expectation is a suitable strategy for PF (Hergert et al. 1997).

More dynamic and real-time PF approaches are currently being investigated. Soil-crop simulation models are increasingly used to evaluate management options, but this often involves empirical calibration of models to local conditions and then simulating effects of spatial and temporal variation on crop growth at the sub-field level (Basso et al. 2001; Batchelor et al. 2002; Sadler et al. 2000). Real-time forms of N management are emerging, in which remote sensing or on-the-go crop sensors are used to drive variable-rate N applications at few critical growth stages. These technologies are not yet widely used by farmers and available research data do not allow a thorough evaluation yet. In dryland wheat (Raun et al. 2002), for example, sensor-based N management did not result in significant differences in yields and nitrogen use efficiency (NUE) if compared to the most profitable conventional management (Table 1).

Table 1. Examples of proactive (p) or corrective (c) site-specific N management approaches.

Crop, location	N treatment[1]	Decision tools[2]				N applied	Yield	NUE[3]
		S	M_r	M_t	D	kg ha^{-1}	t ha^{-1}	kg kg^{-1}
Maize, NE, USA[4]	Conventional	x	-	-	-	142	10.3	73
	Site-specific 1 (p)	x	-	-	-	141	10.4	74
	Site-specific 2 (p)	x	-	-	-	113	10.2	90
Maize, CO, USA[5]	Conventional	x	-	-	-	152	12.8	84
	Site-specific 1 (p)	x	-	-	-	163	12.4	76
	Site-specific 2 (p)	x	-	-	-	109	12.9	118
Wheat, triticale, Germany[6]	Conventional	x	-	-	-	175	9.2	53
	Site-specific (p)	x	-	-	-	166	9.1	55
Wheat, UK[7]	Conventional	x	-	-	-	174	7.4	43
	Site-specific (p)	x	-	-	-	155	7.2	46
Wheat, OK, USA[8]	Conventional	-	-	-	-	90	2.1	23
	Site-specific (c)	-	-	-	x	109	2.3	21

Wheat, Germany[9]	Site-specific 1	x	-	-	x	178	6.3	35
	Site-specific 2 (p)	x	x	x	-	138	6.3	46
Wheat, Netherlands[10]	Conventional	x	-	-	-	240	9.4	39
	Site-specific (p)	x	x	x	-	189	9.5	50
Rice, Philippines[11]	Conventional	-	-	-	-	130	7.6	58
	Site-specific (c)	-	-	-	x	87	7.5	86
Rice, India[12]	Conventional	x	-	-	-	142	5.0	35
	Site-specific 1 (c)	-	-	-	x	110	5.0	45
	Site-specific 2 (c)	-	-	-	x	108	4.9	45
Rice, China[13]	Conventional	-	-	-	-	171	6.0	37
	Site-specific (p, c)	x	x	-	x	126	6.4	52

[1] Conventional: uniform N rate and fixed splitting of N (existing recommendation or farmers' practice); Site-specific: various approaches.
[2] Decision tools used: S – assessment of N supply using soil sampling or other techniques; M_r – soil/crop model to predict N rate; M_t – soil/crop model to predict splitting/timing of N applications; D – in-season diagnosis and adjustment of plant N using sensing tools.
[3] Nitrogen use efficiency = kg grain per kg N applied.
[4] Irrigated, average of 13 site-years. Site-specific 1: variable N rates based on a standard N prescription utilizing a uniform yield goal and grid maps of soil nitrate and soil organic matter; site-specific 2: reduced variable N rate, 15 to 25% less than site-specific 1 (Ferguson et al. 2002).
[5] Irrigated, one site, two years. Site-specific 1: variable N prescription based on a uniform yield goal and grid soil sampling. Site-specific 2: variable N prescription based on a variable yield goal and soil sampling by management zones (Hornung et al. 2003).
[6] Two sites, one year. Both N approaches included three N applications. Site-specific: variable N rates adjusted according to management zones with different expected yield and soil characteristics (Ebertseder et al. 2003).
[7] Six site-years. Site-specific: variable N adjusted to management zones with different yield goal based on yield map history (Welsh et al. 2003b).
[8] Dryland, average of four sites, one year. Conventional: 45 kg N ha^{-1} preplant + 45 kg N ha^{-1} midseason; Site-specific: 45 kg N ha^{-1} preplant + variable sensor-based midseason amount at 1-m spatial resolution (Raun et al. 2002).
[9] One site, two years, Site-specific 1: soil test-based preplant N + two variable rate applications using on-the-go Hydro N sensor; Site-specific 1: HERMES simulation model used for determining grid-cell specific N recommendations (Kersebaum et al. 2003).
[10] Two site-years. Site-specific: timing and rates of N based on simulated change in NO_3-N by management zones (van Alphen and Stoorvogel 2000).

[11] Irrigated, average of four crops at two sites. Site-specific: no preplant N, field-specific post-emergence N doses based on weekly chlorophyll meter readings using a SPAD threshold of 35 (Peng et al. 1996).
[12] Irrigated, average of 20 sites in Tamil Nadu, 1998 DS. Conventional: soil-test based N recommendation; Site-specific 1: no preplant N, field-specific post-emergence N doses based on weekly chlorophyll meter readings using a threshold of 35; Site-specific 2: no preplant N, field-specific post-emergence N doses based on weekly leaf color chart readings using a threshold of 4 (Balasubramaniam et al. 2000).
[13] Irrigated, 21 sites x 6 consecutive rice crops, Zhejiang Province, China. Conventional: farmers' fertilizer practice; Site-specific: field-specific NPK rates pre-determined using a simple model; in-season adjustment of N rates at key growth stages using a chlorophyll meter (Wang et al. 2004).

Nitrogen management in cereal systems in Northern Europe

Yields of rainfed winter cereals in Europe are high and so is nitrogen use. Estimates for the UK (Pretty et al. 2000) and Germany (Schweigert and van der Ploeg 2000) suggest that the societal costs of excessive N fertilizer use are large. In Denmark, application of N is already based on a quota system, in which only a fixed amount of N can be applied, which is even below the economic optimal application level. Thus, achieving higher NUE, by reducing unproductive N inputs or optimising the application of a given amount of N, has been at the heart of many PF attempts in this region. We mainly summarize lessons learned from research conducted in the UK, but similar activities are ongoing in Germany, Denmark, and other countries.

The UK project was conducted over five years (1996 to 2001) in southern England to determine guidelines for maximizing profitability and minimizing environmental impact of cereal production by using PF (Blackmore 2000; Welsh et al. 2003a; Welsh et al. 2003b; Wood et al. 2003). Similar to many PF approaches in North America, it set out to (i) explore the extent and causes of variation within fields, (ii) develop techniques to measure variation during the course of the growing season, and (iii) develop methods of informing the grower of the potential benefits of PF. Yield maps were found to be indispensable for targeting areas for investigation and treatment by PF practices. They provided a basis for estimating replenishment levels of P and K fertilisers, but not for determining a variable N application strategy to optimise management in a particular season. Extent and potential causes of yield variation were determined using yield mapping together with electro-magnetic induction techniques to assess variation in soil factors such as texture and water holding capacity. Within-field management zones were delineated from this information as the only cost effective method for commercial use. Variability within a field was, however, difficult to predict when using several seasons of yield mapping. Fields should therefore be managed also according to the current year's conditions rather than by the use of historic yield maps alone. It was found necessary to combine real-time data on relative crop canopy structure obtained by remote sensing and ground truthing with existing models of N response to successfully adjust N input levels for optimising yield response. The spatial variation in canopy development was estimated using a digital air photograph technique, either within a field or at the farm scale. This also guided herbicide and plant growth regulator applications. Unless nutrient deficiencies were severe, the current techniques of soil and tissue analysis did not provide useful information to assist in interpreting the causes of yield variation within a field.

The application of N in a spatially variable manner improved the efficiency of cereal production through managing variations in the crop canopy. Depending upon field and year, between 12% and 52% of the area of fields under investigation responded positively to this approach. Spatially variable application of N had an overall effect on reducing the N surplus by approximately one third and produced an overall benefit of €36 ha^{-1} compared to a standard N management policy. At current prices, a farmer with 250 ha of cereals where 20% of the farmed area could respond positively to spatially variable N would need to achieve a yield increase of 1.1 t ha^{-1} on that 20% to break even for a PF system costing €18400. The net effect of combining the benefits of spatially variable application of N with the benefits from both the spatial application of herbicides and fungicides should provide valuable returns from the adoption of PF. However, before PF is adopted, routine agronomic and management practices must be optimised because otherwise they can undermine financial benefits from PF. Entering precision farming is a stepwise procedure.

Overall, findings in the UK project were similar to those made in North America and other countries where PF concepts have been developed. Because optimum N rates vary spatially along with seasonal conditions, spatially variable N management without the use of season-specific information on the crop is unlikely to achieve much benefit. More emphasis is currently given to real-time methods of N management using on-the-go sensing of crop “greenness” or soil-crop simulation models. Results obtained so far suggest that significant reductions in N use are feasible, whereas increases in yield or protein content are small (Table 1).

Crop management in dryland wheat systems in Western Australia

The dryland wheat belt of Western Australian exemplifies how farmers adopt PF technologies with the purpose of managing high risk, low input systems. This is an extensive, export-oriented, grain-legume system that faces significant production risk against a backdrop of declining terms of trade (Chisholm 1992). Yield is strongly related to the amount of water that is received in any given growing season (French and Schultz 1984). Price risk occurs because grain products are sold on world markets that fluctuate widely. Investment is moderated by risks. Over 80% of growers adopt major risk management strategies such as drought proofing, hedging or off-farm investment. These difficulties are reflected in the average wheat yields, which, at a little over 1.6 t ha^{-1}, are well below the yield potential. Nevertheless, grains farmers in Western Australia have been the most enthusiastic adopters of PF in Australia. This might seem surprising, since prevailing wisdom is that PF adoption is most rapid where high yield can support the costs of adoption. Three features seem to explain this willingness to adopt: firstly, farmers in Western Australia are responsive to technological advances they believe are necessary to support change; secondly, farmers require information about yield patterns to help manage production risk and thirdly, farmers require technology to ease operational difficulties of managing large areas with low labour inputs (Cook and Bramley 1998).

While different sectors have adopted technology in a variety of forms and to varying degrees, from the Australian perspective the term ‘precision farming’ means a single underlying change in management: improving the precision of the system used to control crop production (Cook and Bramley 1998). It is generally accepted that real change occurs when a farmer knows how to complete the cycle of increasing precision – through observation, interpretation and decision- that enables variation to be managed more effectively. Until that time, the technology remains little more than a novelty. Yield monitoring was introduced to Australia in 1993. Initial yield maps revealed a degree of variation in grain yield that surprised farmers, and encouraged more to buy. While some general approaches of PF – mostly based on concepts imported from the U.S. – have been offered, these have largely been rejected. Farmers seem to develop their own forms of adoption. The common objective is to reduce unwanted variation through better targeting of inputs and tighter control of field operations. In practice, this takes the following forms: (1) permanent removal of persistently poor-performing sectors of paddocks from cropping, (2) spray guidance to reduce overlaps or spray misses, (3) modified whole-paddock management on the basis of detailed quantitative observations of crop performance (e.g., increases or reductions in fertilizer rates), (4) sub-paddock zoning of fertilizer according to predictions of yield potential from satellite imagery, and (5) on-farm experimentation.

In the mid 1990?s the number of yield monitors and differential GPS units expanded fairly rapidly in the expectation of easy gains from the information. About 500 yield monitors were sold to farmers in Western Australia, mainly to larger farms (> 2000 ha.). Experience showed that farmers quickly developed individual expectations from the technology, moving to more immediate and robust concepts such as machine guidance and zone targeting of fertilizer. Local technology providers developed world-class competence in GPS guidance technology, and satellite imagery interpretation. Researchers and farmers demonstrated early on the feasibility of using on-farm experiments as an operational farm management tool. Through early results they demonstrated that economic gains were feasible through both conventional and variable-rate treatments. On the negative side, precision farming has failed to deliver many of the promises that looked reasonable over 10 years ago. The exogenous, prescriptive solutions to varying fertilizer applications have proved largely unworkable, partially because of the prohibitive cost of grid sampling over such huge areas. Alternative options of management zones, based less on yield maps than on satellite imagery have a small but significant client base. Farmers showed much interest in on-farm experimentation, but the shortage of advisers capable of supporting the process has frustrated progress (Cook and Bramley 1998).

Future directions for PF in Western Australia are highly dependent on external factors such the development of technology, the conditions of world markets or the insistence of buyers on product standards - all of which are beyond the control of Australian growers. Two features seem likely to expand. First, quantification of key drivers of variation, especially the dependence of yield on available water, seems within reach. Robust methods of applying simulation models over large areas are available that do not rely on detailed soil maps (Pracilio et al. 2003). Second, expansion of the role of farm improvement groups is increasing. Such groups have been part of Australian agriculture since the early 90's. They may become the organizational hub of change and provide a focus for learning and development of advanced farming techniques.

Nutrient management in irrigated rice systems in Asia

In irrigated rice systems of south and southeast Asia, farms and individual fields are small. Only small equipment can be used. In the early stages of the Green Revolution, response to N, and later also P, was nearly universal. Blanket approaches have dominated rice nutrient management in the past. Fertilizer N recovery efficiencies average only 30 to 40%, unbalanced plant nutrition occurs, and yield growth has stagnated since the mid-1980s in some of the most important regions (Dobermann and Cassman 2002). Revitalizing yield growth, increasing profitability, and sustaining soil fertility are key targets for farmers in these environments. On-farm studies demonstrated that major uncertainties were caused by variability occurring among small fields in the supply of nutrients from indigenous sources and, consequently, the response to fertilizers (Angus et al. 1990; Cassman et al. 1996; Dobermann et al. 2003a). Soil tests are of less use for predicting this variability because they fail to account for the dynamics of nutrient supply under submerged conditions and do not measure nutrient inputs from other indigenous sources such as irrigation or N fixation (Dobermann et al. 2003b). Site-specific management in these environments has focused on managing nutrients at the scale of a single, small field, including in-season N management decisions.

One line of research has focused on corrective, in-season N management using tools such as a chlorophyll meter (Peng et al. 1996). Typically, this involves no or a small application of N before planting and assessing leaf N status ("greenness") in intervals of 7 to 10 d beginning from mid-tillering stage of rice. Each time, a decision on whether to apply N is made, which requires local calibration to empirically define thresholds and suitable N amounts. A simple leaf colour chart (LCC) can replace the chlorophyll meter in this approach (Balasubramaniam et al. 1999; Furuya 1987; Singh et al. 2002; Yang et al. 2003). Evaluation of these methods has generally shown that the same rice yield can be achieved with about 20 to 30% less N applied, whereas increases in yield are less common or relatively small (Table 1). The gains in NUE are usually large. There are, however, risks involved: leaf colour is not only a function of N nutrition, the decision on when and how much N to apply remains empirical, periods of deficiency may occur in between diagnosis events, decisions about early-season applications of N and other nutrients must be made using other means, sampling and measurement errors may occur, and the LCC reading may have misrepresentative colour tones.

Some of these uncertainties were addressed in a broader concept for site-specific nutrient management (SSNM), which integrated information collected at different scales for making field-specific decisions on N, P, and K management (Dobermann et al. 2004). Key components are measurement of grain yield in nutrient omission plots to obtain field-specific estimates of the indigenous supply of N, P, and K (Dobermann et al. 2003b), a decision support system for predicting total NPK requirements and N splitting patterns before planting, and in-season upward or downward adjustments of pre-determined N doses at critical growth stages, based on chlorophyll meter or LCC readings. Variations in crop nutrient requirements due to regional differences in yield potential, location-specific crop management practices, and the overall nutrient input-output balances are taken into account in addition to spatial variation in indigenous nutrient supply.

From 1997 to 2000, this strategy was evaluated in permanent on-farm experiments at 179 sites in eight irrigated rice domains of Asia (Dobermann et al. 2002). On average, grain yield increased by 11% and the N fertilizer rate decreased by 4% as compared to the baseline farmers' fertilizer practice. Average profit increased by US$46 ha^{-1} per crop cycle (12%) and the recovery efficiency of fertilizer N increased from 30% to 40%. Benefits of SSNM varied widely among sites and were strongly affected by the overall crop management quality, particularly crop establishment, water management, and pest control. Average yield increases ranged from 0.1 to 0.6 t ha^{-1} among the eight rice domains studies. SSNM was most profitable at sites in China, southern India, and the Philippines, with average profit increases ranging from US$57 to 82 ha^{-1} per crop in those domains. The performance of SSNM improved over time due to a gradual learning process and re-capitalization of investments in P and K applications made in the first year. Extra costs and other socio-economic issues may complicate the adoption potential of SSNM, but the gains in profitability appear to be attractive enough for farmers. More recent data show remarkable consistency of increases in yield, profit and NUE (Fig. 1). The two approaches described above were recently integrated in a flexible framework of simple SSNM Asia, including nationwide initiatives in several countries. Distribution of LCC has increased from 25000 in 2001 to 280000 in 2003 (R. Buresh, IRRI, personal communication).

Barriers to adoption of precision farming

After about 15 years of research, assessing the potential of PF remains difficult, both in terms of its impact on farmers and in terms of the underlying agronomic principles that hamper faster progress. Examples of success have been reported, but well-documented improvements in yields, profitability or environmental quality remain rare in the scientific literature. Lambert and Lowenberg-DeBoer (2000) reviewed 108 articles published in the scientific and popular literature reporting economic results of PF based on either simulated responses or actual field studies. Most reports (73%) focused on VRT and 63% claimed higher profits. However, many studies omitted important costs such as soil testing, data analysis, or training. Only 40% of all articles provided actual field evaluation results. Only three articles were field studies published in peer-reviewed scientific journals in which site-specific treatments were implemented over several years, with appropriate measurements of the agronomic, economic, and environmental impact.

In general, adoption of PF in North America, Europe, Australia and other parts of the world has progressed patchily. Worldwide, yield monitors have clearly outpaced the adoption of other PF components. More than 30000 yield monitors are currently in use in North America, 800 in Australia, 800 in Latin America (mostly in Argentina), and about 1300-1500 in Europe (J. Lowenberg-DeBoer, personal communication). About 40% of the U.S. corn acreage, 30% of the soybean area, and 15% of the wheat area are harvested with yield monitors, but only about one-third of these combines have mapping capabilities.

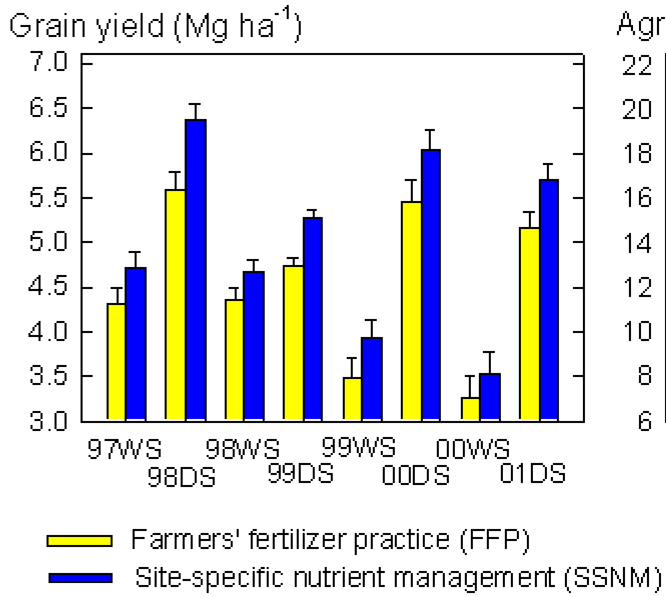

Figure 1. Gains in irrigated rice yield and the agronomic efficiency of fertilizer-N (kg grain yield increase per kg fertilizer-N applied) through site-specific nutrient management in Nueva Ecija province, Philippines. Values shown are means and standard errors of the same 27 fields managed from 1997 to 2001, including wet (WS) and dry (DS) season rice (Source: RTOP Project database, IRRI).

In Denmark, about 400 farmers have adopted some PF practices, but only few can do a range of PF applications themselves (Pedersen et al. 2003). Dealers in the U.S. estimated that 20% of their market area received GPS-guided soil sampling, 11% variable single-nutrient applications, and 15% variable rate liming (Whipker and Akridge 2003). Nearly 70% of U.S. retailers providing agronomic services use at least some PF technologies. Most common services offered include georeferenced soil sampling, data analysis, agronomic recommendations, and variable rate fertilizer application. Variable seeding, pesticide application, or remote sensing are other technologies used, but their adoption varies widely.

Transgenic crops entered the U.S. market at about the same time (1995) as many PF technologies, but are now grown on 40% of the maize and 81% of the soybean area (www.ers.usda.gov/data/BiotechCrops). Unlike new varieties that mostly carry embodied knowledge, PF involves significant investments in hardware, software and human capital development. Steep learning curves must be mastered and additional costs cannot be recovered easily. Making PF profitable (42%), reducing the cost of adoption (28%), finding and keeping good people (21%) and selling the "idea" (11%) were named as the biggest challenges for PF by agricultural businesses surveyed in the U.S. (Whipker and Akridge 2003). Surveys of early adopters in the USA, Denmark and the UK showed that many producers are quite optimistic about increased input use efficiency and profitability with precision agriculture, but think that it will take 5-10 years to achieve their expected level of profitability (Pedersen et al. 2001; Pedersen et al. 2003). Interestingly, most respondents in these surveys collected information using PF technologies, but have not used it yet to change farm management practices (Fountas et al. 2003). Farmers found soil maps and yield maps potentially useful for making decisions and cited variable rate application of fertiliser the practice expected to most likely increase profits on their farm. The greatest disincentive to adoption of PF was the cost of the equipment coupled with a current lack of evidence of increased yields, profits or environmental benefits. Another major disincentive was the time required to work on the data. Factors such as farm size, full-time farming, and computer literacy positively influence the likelihood of PF adoption (Daberkow and McBride 2003). In Australia, adoption of PF may have been slow not because of lack of benefit or by conservatism on the part of the farmer, but by difficulties of delivering these technologies through groups such as crop advisors (Cook et al. 2000).

Producers want cost effective, easy to use, integrated PF systems and more thorough and scientifically based advice. Developing them requires understanding of decision processes and sources of uncertainty in the context of site-specific management problems (Adams et al. 2000). In data poor situations, knowledge-driven models may be less accurate but preferred by the farmer, while in data rich situations data-driven models may be more appropriate. Considerations for this involve: (1) Is the information *deliverable* and what change in management could result from more information and control? (2) Is the information *new*? (3) Is the information *significant* to the person who makes the decision? (4) Is the information *actionable*: given that I believe this variation to be significant and that I am certain enough about the causes (likely outcomes of change), then I will change. This is by far the most difficult barrier to overcome. If a farmer is not certain enough to take sub-field action, he may still consider making whole-field changes.

High costs and knowledge demand, unavailability of many services, and uncertain benefits seem to preclude any possibility of PF in developing countries. However, the basic purpose of PF - to provide spatial and temporal information to reduce uncertainty – should be viewed as essential to accelerate change in the developing world, even if it is used in a different form to that offered in Europe or North America (Cook et al. 2003). The need for spatial information is actually greater in developing countries, principally because of stronger imperative for change and lack of conventional support. A large body of spatial information exists in the developing world, much of it freely available. The challenge lies in overcoming issues of scale and uncertainty, and finding meaningful ways of delivering this information to farmers. Promising approaches are those in which farmers create their own local spatial data at appropriate scales. One example for this is the SSNM concept developed for rice (see above) using a combination of regional and local information. Other examples include sugar cane growers in Colombia who have organized themselves to use spatial information for site-specific management, site-specific natural resource management at catchment and community scale, or participatory three-dimensional mapping, in which a terrain model is the basic information source, generated by the local community itself (Cook et al. 2003). In export-oriented cash crops, PF may be similar to that in developed countries. First examples of this have emerged for fruit, tea, or oil palm plantations. The much reduced cost of labour may in fact enable developing countries to obtain spatial knowledge at a lower cost than in developed countries.

Future directions for precision farming

A field can rarely be made "uniform" with regard to crop performance, but PF has the potential to adjust the scale of management to the scales at which most of the decision uncertainty occurs. Initial approaches in which the focus has been on managing sub-field spatial variability through yield mapping, georeferenced soil sampling, remote sensing, GIS data management, and VRT have had limited success. In nutrient management, reasons for failure often include: (i) poor sampling strategies causing high costs and insufficient characterization of spatial and temporal variation in indigenous nutrient supply, (ii) use of prescription algorithms that are not suitable for site-specific management, and (iii) lack of post-emergence adjustments in N management to account for the actual climatic conditions and yield potential. Errors are caused by unresolved spatial variation (undersampling, measurement errors, and inappropriate interpolation), uncertainty about crop response models, and inaccuracy of VRT equipment. Attempts to explain crop yield variability as empirical functions of soil properties or landscape features, have, in most cases, accounted for less than half of the crop growth variation observed. There are also no clear guidelines for how to derive and interpret functional management zones for different decisions. Is it reasonable to vary inputs by zones only or should one aim for a combination of larger zones with continuously measured data that express crop yield determinants at the spatial and temporal scales at which they occur?

In recent years, emphasis has shifted to developing more dynamic, integrated forms of site-specific management. Such future solutions focus on more flexible characterization of factors that determine crop performance and input use efficiency. Some decisions require fine spatial resolution but little in the way of characterizing temporal variability. A typical example for this would be location-specific alleviation of soil compaction. Other decisions require a combination of quantitative predictions and real-time data acquisition methods because both spatial and temporal variability may be significant. In crops, climate, water and nitrogen belong to this category because they are the key determinants of growth and yield. Real-time canopy control strategies will require predicting yield as a function of climate, water and N supply during the growing season. The greatest level of detailed understanding will probably pay most in high-value crops, where more precise management can improve both the quantity and quality of crop production.

Future PF solutions may include many in which data acquisition, decision-making, and action are done in near real-time, often also at fine scales of management. Innovative experimental approaches, remote sensing, soil and plant sensors, crop simulation models, equipment guidance, and even small autonomous field robots will play an increasing role in characterizing variability, evaluating its significance, and executing variable soil and/or crop treatments.

Innovative field experimentation

While adoption has been patchy, where farmers actually take up PF technology, they have done so quickly, presumably in the expectation that advisers could help them benefit from the mass of information it generates. There is little evidence, however, that agronomy has applied its analytical power to the explanation of yield variation as shown, for example, in yield maps. This seems strange because yield maps provide detailed observations of crop yield variation - the very thing that field crop science has spent decades trying to explain. Yet few experiments reported in agronomy journals use them.

Three reasons may explain this, all of which relate to the contrast between the perception of a field as a business unit and as an object of scientific study. First, for practical reasons crop experimentation has largely restricted observations to small areas. This approach clarifies the effects of management treatments, but effects of factors such as geology, soil, topography, pests or diseases only become apparent beyond the plot scale. These features dominate variation in yield maps. Second, the basic analytical tools that give agronomy its power also *obstruct* full explanation of soil variation in yield because classical methods clarify treatment effects by removing the variation due to *site* (McBratney 1985). Yield maps contain just one ‘treatment’, but show huge variation. Third, the conceptual model of experimental science seeks to explain phenomena according to scientific concepts that are generally true, whereas operations research adopts a more humble aim of explaining how a managed system is likely to behave under uncertainty. An approach that avoids some of these problems is to characterize the experimental system at the scale of the business unit - the field. On-farm experimentation is feasible using PF technology to modify inputs and measure the effect on yield over entire fields and over time. Experience in Australia shows that farmers feel comfortable experimenting over entire fields. Innovative approaches and practices for using PF technologies in on-farm experimentation have been developed (Bramley et al. 1999; Lark and Wheeler 2003).

Remote sensing

Remote sensing provides a great deal of fundamental information relating spectral reflectance and thermal remittance properties of soils and crops to their agronomic and biophysical characteristics at scales that may range from small patches within a field to large regions (Pinter et al. 2003). This makes it an attractive tool for site-specific decisions in many environments, particularly with regard to soil characterization, non-destructive monitoring of plant growth, and detection of environmental stresses which may limit crop productivity. Key developments in recent years include rapidly increasing availability of remote sensing technologies and substantial improvements of the spatial and spectral resolution. For example, commercial satellites such as Quickbird (www.digitalglobe.com) or IKONOS (www.spaceimaging.com) are now available with spatial resolutions of 2.4 or 4 m multi-spectral and 0.6 or 1 m panchromatic. Those as well as similar airborne imagery allow mapping patterns of soil and vegetation with greater detail than that obtained by yield monitors or soil sampling, and without convolution inconsistencies. Numerous studies have demonstrated associations between crop canopy reflectance, crop biomass, leaf area index, and crop yield at different spatial scales. The strength of remote sensing is the opportunity to learn more about crop growth variability while the crop is still growing. Benefits can be realized by combining this information with soil and yield maps or crop models in developing an integrated crop management program. The major challenge to be tackled in the future is that of making the interpretation process more automatic, generic, and mechanistic rather than relying on empirical, location-specific remote sensing solutions for crop management.

Soil and plant sensors

The present lack of reliable and inexpensive sensors has been seen as a major obstacle to the adoption of PF (Sylvester-Bradley et al. 1999). Although there is a large variety of design concepts, most on-the-go soil (Adamchuk et al. 2004) and plant sensors involve one of the five measurement principles shown in Figure 2. Electrical and electromagnetic sensors measure electrical resistivity/conductivity, capacitance or inductance affected by the composition of the material tested. Optical and radiometric sensors use electromagnetic waves to detect the level of energy absorbed, transmitted, or reflected by soil particles or plant tissue, or use machine vision systems to identify different plant species or measure plant density in real time. Mechanical sensors measure forces resulting from a tool engaged with the soil or quantify the plant's ability to resist mechanical impact, for example to estimate crop biomass or plant density. Acoustic sensors quantify the sound produced by a tool interacting with the soil, whereas pneumatic sensors assess the ability to inject air into the soil, and both types have been used as a proxy for soil compaction. Electrochemical sensors use ion-selective membranes that produce a voltage output in response to the activity of selected ions in soil solution.

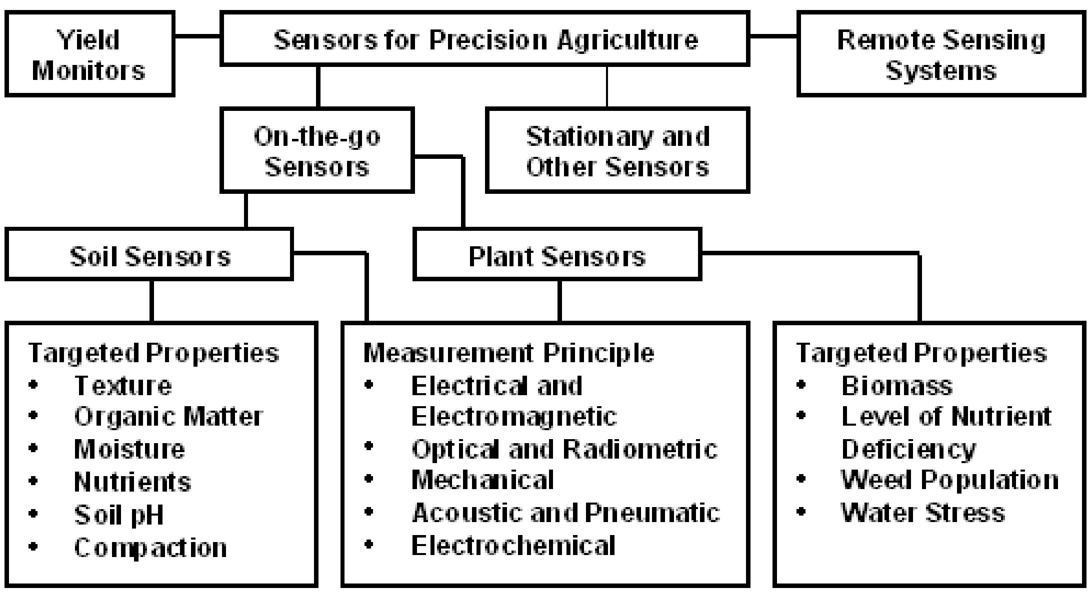

Figure 2. On-the-go soil and plant sensors as part of the family of sensors used in precision agriculture.

Although producers would prefer sensors that provide direct inputs for existing prescription algorithms, the reality is that most available sensors provide only indirect measurements of soil or plant attributes. They serve as useful relative indicators of field soil and/or plant heterogeneity. For example, variation in measured soil electrical conductivity is mainly caused by variation in salinity, soil texture, soil moisture, and organic matter content (Corwin and Lesch 2003). Although maps of electrical conductivity are useful in terms of showing up-to-date patterns and boundaries of soils within a field, their interpretation with regard to spatial variation in soil nutrients or crop yield tends to be location-specific (Kitchen et al. 2003). A major use of soil sensors is to provide spatially dense data layers at relatively low cost. This information can be used in combination with other data (soil sampling, crop scouting, yield maps, digital elevation models, remote sensing) to (i) divide a field or landscape into smaller sub-units (e.g., management zones), (ii) guide soil sampling, and (iii) improve the precision of maps of primary attributes if those are correlated with data layers obtained from sensors (Fig. 3). More robust mapping algorithms must be developed for these tasks, including pedo- or phytotransfer functions that will allow converting sensors outputs into meaningful decisions. There is also some potential for developing new sensors that provide direct measurements of soil attributes. Direct soil mapping using ion-selective electrodes has shown good results for pH, whereas mapping of nutrients such as NO_3-N or K appears to be less promising (Adamchuk et al. 2003).

Much research has been conducted to develop optical sensors that measure reflectance or absorption of light by leaves or the entire crop canopy to facilitate adjustments of crop management during growth. On-the-go sensing of crop reflectance at wavelengths that are sensitive to biomass and/or leaf greenness has received much recent attention, particularly within the context of real-time, in-season N management (Raun et al. 2002; Schmidthalter et al. 2003). Current technologies vary in terms of types of sensors used, sensor configurations (number, hight, angle, etc.), spectral and spatial resolution, wavelength indices used for interpretation, and decision algorithms. Most real-time crop sensing and N application systems are corrective N management concepts in which vegetation indices for estimating crop biomass and N status must be identified and translated into decisions for N fertilizer needs (Schroeder et al. 2000). Often, greenness is compared with that in a well-fertilized reference strip to empirically assess whether a deficiency has occurred and whether an additional yield response to N is likely to occur or not.

So far, most field studies in which sensor-based N management systems were compared with other forms of N management have indicated significant increases in N use efficiency due to savings in N amounts (often 10-20% less N), with either no or only small increases in yield. This raises questions about the profitability of this approach, particularly when the full cost of sensor-based N management is included. Better returns may be obtainable in crops for which site-specific N management leads to better product quality. Overall, however, uncertainties include that “crop greenness” is affected by numerous factors other than N and that sensing can only be done occasionally after the crop has developed enough biomass. Nitrogen deficiency may occur during early vegetative growth, which cannot be corrected with late-season N applications. Therefore, integrating proactive and corrective decisions for quantifying how much N must be added when remains the major scientific challenge in this approach.

Commercialisation of on-the-go soil and crop sensors has begun. Among soil sensors, electrical and electromagnetic sensors have been used most widely, for example in mapping systems developed by Veris Technologies, Inc. (www.veristech.com), Geonics Ltd. (www.geonics.com), Geocarta (www.geocarta.net), and Crop Technology, Inc. (www.soildoctor.com). A mobile sensing platform for combined mapping of soil pH and electrical conductivity has recently become commercial as well (www.veristech.com). Among plant sensors, commercial developments include two on-the-go sensing and variable rate N application systems, the Hydro N-sensor (www.sensoroffice.com) and the GreenSeeker? system (www.ntechindustries.com). Sensor-based management of herbicides and other crop protection chemicals represents another promising application of sensor technology (Timmermann et al. 2003).

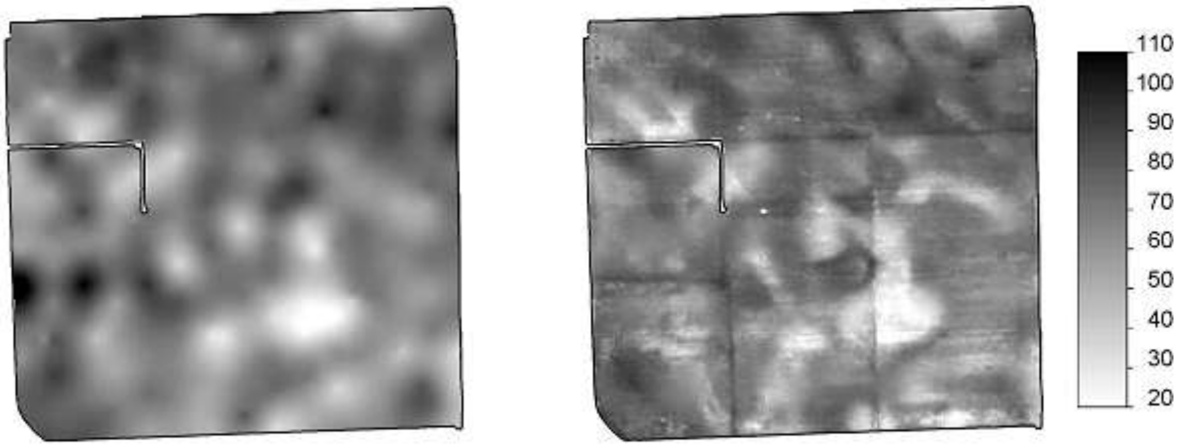

Figure 3. Maps of soil organic carbon (t C ha^{-1} in 0-30 cm depth) in a 64-ha field at Mead, Nebraska. LEFT: ordinary kriging interpolating of soil C measured at 265 locations. RIGHT: regression kriging interpolating of soil C measured at 132 locations in combination with sensed maps of soil electrical conductivity, soil surface reflectance, and elevation. Although only half the number of soil samples was collected, the regression kriging map showed finer details and resulted in a relative increase in map precision of 33% over ordinary kriging (G. Simbahan and A. Dobermann, unpublished data).

Weed detection has been of particular interest in recent years (Felton et al. 2002) and commercial solutions such as the WeedSeeker? system (www.ntechindustries.com) have been adopted by some crop growers, as well as by users outside of agricultural production (e.g., railroad transportation). Sensors under development vary from simple colour detectors to complex machine vision systems, whose ultimate goal is to use colour, shape and texture features of plant material to separate weeds and crops as well as to identify populations of different weed species. Such sensors may also offer new possibilities for detecting general early-season growth differences, with potential applications in selecting suitable crop cultivars, as indicators of crop nutrient status, in plant disease management, in weed mapping, and for studying temporal changes in crop biomass dynamics (Felton et al. 2002). Grain protein sensors are another important emerging technology (Thylen et al. 2003) that is likely to expand yield mapping capabilities to issues of product quality.

Soil – crop simulation models

Crop simulation models or even more complex soil-landscape-crop simulation models are increasingly used in PF research, but their complexity has often hampered the use of modelling in making practical decisions on input use (Angus et al. 1993). Many recent modelling efforts have focused on understanding spatial variability at the sub-field level and simulating scenarios for SSCM (Booltink et al. 2001). The challenge is to make these models robust enough for practical decision-making, limit the amount of input variables needed, minimize the need for local “model calibration”, and use models for exploring management options *a priori* as well as in *real-time* during the growing season.

In-season forecasting of crop biomass and yield is becoming possible and first applications have emerged (Bannayan et al. 2003). The example in Fig. 4 illustrates this approach for maize grown at two sites in Nebraska. This study and others have shown that relative deviations from average growth can be detected during vegetative growth, whereas final yields can be predicted with reasonable certainty once the crop reaches about flowering stage. Such information is useful for making both tactical management adjustments and marketing decisions. Combining models in real-time with additional measurements of actual field growth or remote sensing may allow improving yield forecasts or making them earlier during the growing season (Guerif and Duke 2000), but most models will have to be modified for this purpose.

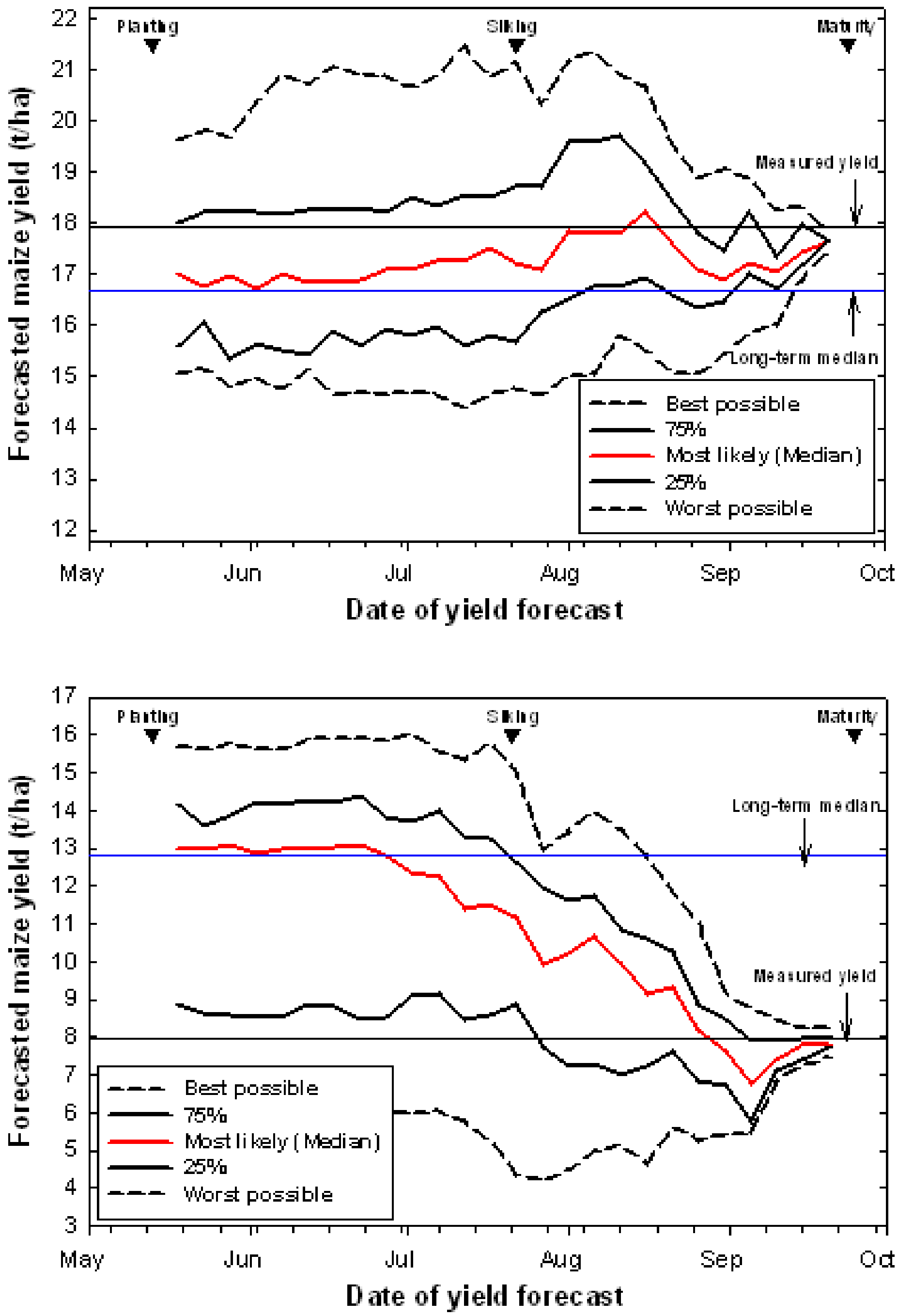

Figure 4. In-season forecasting of maize yields in two fields in Nebraska, 2003. LEFT: Irrigated maize grown under optimal conditions at Lincoln. RIGHT: Rainfed maize grown under drought stress at Mead. At both sites, maize was planted on May 13 and daily weather data were used to simulate actual growth. Growth scenarios for the remainder of the season were forecasted from long-term weather data. Forecast were made every five days during the growing season using the Hybrid-Maize model (Yang et al. 2004). No model calibration was done.

Models should also play a major role in improving water and nitrogen management by more quantitative prediction of crop yield, water and N needs during the growing season (Booltink et al. 2001; Kersebaum et al. 2003; van Alphen and Stoorvogel 2000). There are also opportunities for using simplified crop models in site-specific management, particular with regard to making nitrogen decisions before planting and during early growth. Ten Berge et al. (1997), for example, used a simple model to determine both the amounts and the timing of N applications at the beginning of the cropping season, resulting in 5 to 10% yield increases of irrigated rice. Generic empirical models describing the dilution of optimal N concentrations with increasing crop biomass for a certain yield target (Greenwood et al. 1990) could be used in conjunction with actual weather data and sensed crop reflectance to make quantitative N application decisions on-the-go.

Some attempts have been made to develop mechanistic models of the complete soil-plant P or K cycle (Daroub et al. 2003; Greenwood et al. 2001; Greenwood and Karpinets 1997; Karpinets et al. 2004), but simpler models such as locally improved versions of the QUEFTS model (Janssen et al. 1990; Witt and Dobermann 2004) may be sufficient for making site-specific P and K decisions.

Guidance systems and autonomous machines

The civil use of the Global Positioning System (GPS) has been one of the driving forces for PF and has also created new opportunities for vehicle guidance in agriculture. Parallel swathing, for example, involves an array of light diodes or a graphical display that warns the operator about errors due to deviations of vehicle location relevant to the predefined field pattern. More sophisticated autoguidance systems have recently become available, which allow following precisely predefined tracks across the field. In this case, the guidance system is used not only to determine navigation errors, but also to correct vehicle steering angle without involvement of the operator. These systems include more accurate GPS and attitude compensation equipment, which makes it feasible to implement different field practices that require precise vehicle guidance. Potential benefits for crop production and the environment mainly arise through the more precise application of inputs, including avoiding overlaps or skips. Examples include more accurate tillage, land levelling for irrigation, planting and plant spacing, mechanical weed control, and application of fertilizers and pesticides. Other advantages include the capability to perform field operations with low outside vision and reduced operator fatigue. Although vehicle guidance is already being adopted widely in some parts of North America, its potential short- and long-term impacts on profitability of farming, soil and environmental quality are not yet documented well.

Sensors and vehicle guidance systems also provide new opportunities for developing autonomous agricultural equipment (Blackmore and Griepentrog 2002). Such systems can behave in a sensible manner for long periods unattended because monitoring, decision-making, and variable rate application capabilities are embedded in them. Only few such prototypes have been developed so far and reliability and safety concerns must be resolved before such machines can be adopted. Recent research in Europe, for example, has led to first prototypes of small, unmanned tractors with intelligent control (API 2003). Ultimately, such vehicles may carry out a range of useful tasks, either alone or collaboratively with other machines. They are capable of receiving instructions and able to work longer hours at a slower rate, giving the same, or even greater, overall output as conventional systems.

Conclusions

The various concepts and technologies that will make up tomorrow's precision agriculture are still emerging. Over the 15 years since PF was introduced, its objectives and capabilities have changed dramatically. Originally, it was mainly seen as a technology to manage heterogeneous fields. The challenges then were seen as developing technologies that would allow mapping spatial variability and adjusting inputs accordingly. Over time, PF has evolved into a general management concept to reduce decision uncertainty caused by uncontrolled variation, with widely ranging applications and scales of management. It became evident that managing temporal variation is as important as managing spatial variation.

The soil and crop science underlying many PF concepts may have lagged behind some of the rapid developments in agricultural equipment and information technologies. Researchers and farmers can easily collect huge amounts of information, but assessing the quality of this information, transforming it into meaningful management decisions, and evaluating potential benefits and risks has proven to be a difficult task. It is up to soil and crop scientists along with agricultural engineers and economists to develop simple and robust methodologies and technologies for farmers so that the full potential of PF can be exploited. They must conduct rigorous evaluation studies at multiple sites and with standardized methodologies, including utilizing PF technologies for gaining a better understanding of crop yield determinants. Proof of economic and environmental benefits must be demonstrated. The widespread use of empirical rules and algorithms must gradually be replaced with more in-depth understanding of cause-effect relationships that determine crop productivity, soil and environmental quality at scales that are manageable through PF.

Better nutrient management alone cannot lead to quantum leaps in yields in systems where upper limits of yield potential are already being approached. There is, however, potential for re-energizing yield growth, increasing the profitability, and reducing negative environmental impacts of agriculture through the use of site-specific management concepts that integrate *a priori* decisions with real-time, in-season decisions. Approaches for this are emerging. Better sensors and more robust, user-friendly decision support models will be required. To find wider-scale acceptance, PF technologies must be kept manageable and result in significant increases in profit, which often requires increasing both yield and input use efficiency. Case studies have shown that PF concepts may benefit crop producers in industrialized as well as developing countries. This could either cause them to reduce the scale of management or simply to improve current (conventional) crop production. Many farmers have shown an interest in PF as they can see that it should work in principle. It must now be demonstrated how theoretical ideas and principles can be put into practice. Good agronomy should accompany, and not be offset by, a PF approach.

References

Adamchuk VI, Hummel JW, Morgan MT and Upadhyaya SK (2004). On-the-go soil sensors for precision agriculture. Computers and Electronics in Agriculture 44, 71-91.

Adamchuk VI, Lund E, Dobermann A and Morgan MT (2003). In 'Precision agriculture'. (Eds. J.V. Stafford and A. Werner), pp. 27-33. (Wageningen Academic Publishers, Wageningen).

Adams ML, Cook S and Corner R (2000). Managing uncertainty in site-specific management: what is the best model? Precision Agriculture 2, 39-54.

Angus JF, Bowden JW and Keating BA (1993). Modelling nutrient responses in the field. Plant and Soil 155/156, 57-66.

Angus JF, de St.-Groth CF and Tasic RC (1990). Between-farm variability in yield responses to inputs of fertilizers and herbicide applied to rainfed lowland rice in the Philippines. Agriculture, Ecosystems and Environment 30, 219-234.

API (2003). Autonomous platform and information system for crop and weed monitoring. (Danish Institute of Agricultural Sciences, Horsens, Denmark). www.cs.auc.dk/api.

Auernhammer H (2001). Precision farming - the environmental challenge. Computers and Electronics in Agriculture 30, 31-43.

Balasubramaniam V, Morales AC, Cruz RT and Abdulrachman S (1999). On-farm adaptation of knowledge-intensive nitrogen management technologies for rice systems. Nutrient Cycling in Agroecosystems 53, 59-69.

Balasubramaniam V, Morales AC, Thiyagarajan TM, Nagarajan R, Babu M, Abdulrachman S and Hai LH (2000). Adaption of the chlorophyll meter (SPAD) technology for real-time N management in rice: a review. International Rice Research Newsletter 25, 4-8.

Bannayan M, Crout NMJ and Hoogenboom G (2003). Application of the CERES-Wheat model for within-season prediction of winter wheat yield in the United Kingdom. Agronomy Journal 95, 114-125.

Basso B, Ritchie JT, Pierce FJ, Braga RP and Jones JW (2001). Spatial validation of crop models for precision agriculture. Agricultural Systems 68, 97-112.

Batchelor WD, Basso B and Paz JO (2002). Examples of strategies to analyze spatial and temporal yield variability using crop models. European Journal of Agronomy 18, 141-158.

Bianchini AA and Mallarino AP (2002). Soil-sampling alternatives and variable-rate liming for a soybean-corn rotation. Agronomy Journal 94, 1355-1366.

Blackmore BS (2000). The interpretation of trends from multiple yield maps. Computers and Electronics in Agriculture 26, 37-51.

Blackmore BS and Griepentrog HW (2002). In 'PreAgro Precision Agriculture Conference'. (Eds. D. Berger, A. Bornheimer, A. Jarfe, D. Kottenrodt, R. Richter, K. Stahl and A. Werner), pp. 131-145. (Center for Agricultural Landscape and Land Use Research, M?ncheberg, Germany).

Bongiovanni R and Lowenberg-DeBoer JM (2000). Economics of variable rate lime in Indiana. Precision Agriculture 2, 55-70.

Booltink HWG, van Alphen BJ, Batchelor WD, Paz JO, Stoorvogel JJ and Vargas R (2001). Tools for optimizing management of spatially variable fields. Agricultural Systems 70, 445-476.

Bramley RGV, Cook SE, Adams ML and Corner R (1999). Designing your own on-farm experiments: how precision agriculture can help. (Grains Research and Development Corporation, Canberra).

Cassman KG, Gines HC, Dizon M, Samson MI and Alcantara JM (1996). Nitrogen-use efficiency in tropical lowland rice systems: Contributions from indigenous and applied nitrogen. Field Crops Research 47, 1-12.

Chang JY, Clay DE, Carlson CG, Clay SA, Malo DD, Berg R, Kleinjan J and Wiebold W (2003). Different techniques to identify management zones impact nitrogen and phosphorus sampling variability. Agronomy Journal 95, 1550-1559.

Chisholm A (1992). Australian agriculture: A sustainability story. Australian Journal of Agricultural Economics 36, 1-30.

Cook SE, Adams ML and Bramley RGV (2000). In 'Proceedings of the 5th International Conference on Precision Agriculture and Other Resource Management, July 16-19, 2000, Bloomington, MN. [CD-ROM]'. (Eds. P.C. Robert, R.H. Rust and W.E. Larson) (ASA,CSSA,SSSA, Madison, WI).

Cook SE and Bramley RGV (1998). Precision agriculture - opportunities, benefits and pitfalls of site-specific crop management in Australia. Australian Journal of Experimental Agriculture 38, 753-763.

Cook SE, O'Brien R, Corner RJ and Oberth?r T (2003). In 'Precision agriculture'. (Eds. J.V. Stafford and A. Werner), pp. 115-119. (Wageningen Academic Publishers, Wageningen).

Corwin DL and Lesch SM (2003). Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. Agronomy Journal 95, 455-471.

Daberkow SG and McBride WD (2003). Farm and operator characteristics affecting the awareness and adoption of precision agriculture technologies in the US. Precision Agriculture 4, 163-177.

Daroub SH, Gerakis A, Ritchie JT, Friesen DK and Ryan J (2003). Development of a soil-plant phosphorus simulation model for calcareous and weathered tropical soils. Agricultural Systems 76, 1157-1181.

Dobermann A and Cassman KG (2002). Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant and Soil 247, 153-175.

Dobermann A, Witt C, Abdulrachman S, Gines HC, Nagarajan R, Son TT, Tan PS, Wang GH, Chien NV, Thoa VTK, Phung CV, Stalin P, Muthukrishnan P, Ravi V, Babu M, Simbahan GC and Adviento MAA (2003a). Soil fertility and indigenous nutrient supply in irrigated rice domains of Asia. Agronomy Journal 95, 913-923.

Dobermann A, Witt C, Abdulrachman S, Gines HC, Nagarajan R, Son TT, Tan PS, Wang GH, Chien NV, Thoa VTK, Phung CV, Stalin P, Muthukrishnan P, Ravi V, Babu M, Simbahan GC, Adviento MAA and Bartolome V (2003b). Estimating indigenous nutrient supplies for site-specific nutrient management in irrigated rice. Agronomy Journal 95, 924-935.

Dobermann A, Witt C and Dawe D (2004). Increasing productivity of intensive rice systems through site-specific nutrient management. (Science Publishers, Inc., International Rice Research Institute, Enfield, NH and Los Ba?os, Philippines).

Dobermann A, Witt C, Dawe D, Gines GC, Nagarajan R, Satawathananont S, Son TT, Tan PS, Wang GH, Chien NV, Thoa VTK, Phung CV, Stalin P, Muthukrishnan P, Ravi V, Babu M, Chatuporn S, Kongchum M, Sun Q, Fu R, Simbahan GC and Adviento MAA (2002). Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Research 74, 37-66.

Ebertseder T, Gutser R, Hege U, Brandhuber R and Schmidhalter U (2003). In 'Precision agriculture'. (Eds. J.V. Stafford and A. Werner), pp. 193-198. (Wageningen Academic Publishers, Wageningen).

Felton WL, Alston CL, Haigh BM, Nash PG, Wicks GA and Hanson GE (2002). Using reflectance sensors in agronomy and weed science. Weed Technology 16, 520-527.

Ferguson RB, Hergert GW, Schepers JS, Gotway CA, Cahoon JE and Peterson TA (2002). Site-specific nitrogen management of irrigated maize: yield and soil residual nitrate effects. Soil Science Society of America Journal 66, 544-553.

Ferguson RB, Lark RM and Slater GP (2003). Approaches to management zone definition for use of nitrification inhibitors. Soil Science Society of America Journal 67, 937-947.

Fountas S, Ess DR, Sorensen CG, Hawkins SE, Pedersen HH, Blackmore BS and Lowenberg-DeBoer J (2003). In 'Precision agriculture'. (Eds. J.V. Stafford and A. Werner), pp. 211-216. (Wageningen Academic Publishers, Wageningen).

Franzen DW, Hopkins DH, Sweeney MD, Ulmer MK and Halvorson AD (2002). Evaluation of soil survey scale for zone development of site-specific nitrogen management. Agronomy Journal 94, 381-389.

Franzen DW and Peck TR (1995). Field soil sampling density for variable rate fertilization. Journal of Production Agriculture 8, 568-574.

French R and Schultz G (1984). Water use efficiency of wheat in a Mediterranean-type environment. Australian Journal of Agricultural Research 35, 743-764.

Furuya S (1987). Growth diagnosis of rice plants by means of leaf color. Jpn. Agric. Res. Q. 20, 147-153.

Greenwood DJ and Karpinets TV (1997). Dynamic model for the effects of K-fertilizer on crop growth, K-uptake and soil-K in arable cropping. I. Description of the model. Soil Use and Management 13, 178-183.

Greenwood DJ, Karpinets TV and Stone DA (2001). Dynamic model for the effects of soil and fertililzer-P on crop growth, P-uptake and soil-P in arable cropping: model description. Ann. Bot. 88, 279-291.

Greenwood DJ, Lemaire G, Gosse G, Cruz P, Draycott A and Neetson JJ (1990). Decline in percentage N of C_3 and C_4 crops with increasing plant mass. Ann. Bot. 66, 425-436.

Guerif M and Duke CL (2000). Adjustment procedures of a crop model to the site specific characteristics of soil and crop using remote sensing data assimilation. Agriculture, Ecosystems and Environment 81, 57-69.

Hergert GW, Pan WL, Huggins DR, Grove JH and Peck TR (1997). In 'The site-specific management for agricultural systems'. pp. 283-300. (ASA, CSSA, SSSA, Madison, WI).

Hornung A, Khosla R, Reich R and Westfall DG (2003). In 'Precision agriculture'. (Eds. J.V. Stafford and A. Werner) pp. 297-302. (Wageningen Academic Publishers, Wageningen).

Janssen BH, Guiking FCT, Van der Eijk D, Smaling EMA, Wolf J and van Reuler H (1990). A system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). Geoderma 46, 299-318.

Karpinets TV, Greenwood DJ and Ammons JT (2004). Predictive mechanistic model of soil phosphorus dynamics with readily available inputs. Soil Science Society of America Journal 68, 644-653.

Kersebaum KC, Lorenz K, Reuter HI, Wendroth O, Giebel A and Schwarz J (2003). In 'Proc. 4th European Conference on Precision Agriculture'. (Eds. J.V. Stafford and A. Werner), pp. 309-314. (Wageningen Academic Publishers, Wageningen).

Kitchen NR, Drummond ST, Lund ED, Sudduth KA and Buchleiter GW (2003). Soil electrical conductivity and topography related to yield for three contrasting soil-crop systems. Agronomy Journal 95, 483-495.

Lambert D and Lowenberg-DeBoer J (2000). Precision agriculture profitability review. (Purdue University, West Lafayette, IN). http://mollisol.agry.purdue.edu/SSMC.

Lark RM and Wheeler HC (2003). A method to investigate within-field variation of the response of combinable crops to an input. Agronomy Journal 95, 1093-1104.

Lowenberg-DeBoer J and Aghib A (1999). Average returns and risk characterizations of site-specific P and K management: Eastern corn belt on-farm trial results. Journal of Production Agriculture 12, 276-282.

McBratney AB (1985). In 'Soil spatial variability,'. (Eds. D.R. Nielsen and J. Bouma), pp. 3-8. (Pudoc, Wageningen).

National Research Council (1997). Precision agriculture in the 21st century. Geospatial and information technologies in crop management. (National Research Council (NRC), National Academy Press, Washington, D.C.).

Pedersen SM, Ferguson RB and Lark RM (2001). A multinational survey of precision farming early adopters. Farm Mgmt. 11, 147-162.

Pedersen SM, Fountas S, Blackmore BS, Pedersen JL and Pedersen HH (2003). In 'Precision agriculture'. (Eds. J.V. Stafford and A. Werner), pp. 533-538. (Wageningen Academic Publishers, Wageningen).

Peng S, Garcia FV, Laza RC, Sanico AL, Visperas RM and Cassman KG (1996). Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crops Research 47, 243-252.

Pierce FJ and Nowak P (1999). Aspects of precision agriculture. Advances in Agronomy 67, 1-85.

Pierce FJ and Warncke DD (2000). Soil and crop response to variable-rate liming for two Michigan fields. Soil Science Society of America Journal 64, 774-780.

Ping JL and Dobermann A (2003). Creating spatially contiguous yield classes for site-specific management. Agronomy Journal 95, 1121-1131.

Pinter PJ, Hatfield JL, Schepers JS, Barnes EM, Moran MS, Daughtry CST and Upchurch DR (2003). Remote sensing for crop management. Photogramm. Eng. Remote. Sensing. 647-664.

Pracilio G, Asseng S, Cook SE, Hodgson G, Wong MTF, Adams ML and Hatton TJ (2003). Estimating spatially variable deep drainage across a central eastern wheatbelt catchment, Western Australia. Australian Journal of Agricultural Research 54, 789-802.

Pretty J, Brett C, Gee D, Hine RE, Mason CF, Morison JIL, Raven H, Rayment MD and van der Bijl G (2000). An assessment of the total external costs of UK agriculture. Agricultural Systems 65, 113-136.

Raun WR, Solie JB, Johnson GV, Stone ML, Mullen RW, Freeman KW, Thomason WE and Lukina EV (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agronomy Journal 94, 815-820.

Sadler EJ, Gerwig BK, Evans DE, Busscher WJ and Bauer PJ (2000). Site-specific modeling of corn yield in the SE coastal plain. Agricultural Systems 64, 189-207.

Schmidthalter U, Jungert S, Bredemeier C, Gutser R, Manhart R, Mistele B and Gerl G (2003). In 'Precision agriculture'. (Eds. J.V. Stafford and A. Werner), pp. 615-619. (Wageningen Academic Publishers, Wageningen).

Schroeder JJ, Neeteson JJ, Oenema O and Struik PC (2000). Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Research 66, 151-164.

Schweigert P and van der Ploeg RR (2000). Nitrogen use efficiency in German agriculture since 1950: facts and evaluation. Berichte ?ber Landwirtschaft 80, 185-212.

Singh B, Singh Y, Ladha JK, Bronson KF, Balasubramanian V, Singh J and Khind CS (2002). Chlorophyll meter- and leaf color chart-based nitrogen management for rice and wheat in northwestern India. Agronomy Journal 94, 821-829.

Swinton SM and Lowenberg-DeBoer JM (1998). Evaluating the profitability of site-specific farming. Journal of Production Agriculture 11, 439-446.

Sylvester-Bradley R, Lord E, Sparkes DL, Scott RK, Wiltshire JJJ and Orson J (1999). An analysis of the potential of precision farming in Northern Europe. Soil Use and Management 15, 1-8.

ten Berge HFM, Shi QH, Zheng Z, Rao KS, Riethoven JJM and Zhong XH (1997). Numerical optimization of nitrogen application to rice. Part II. Field evaluations. Field Crops Research 51, 43-54.

Thylen L, Gilbertsson M, Rosenthal T and Wrenn S (2003). In 'Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, MN, USA, 14-17 July, 2002'. pp. 986-999. (University of Minnesota, ASA, CSSA, SSSA, Minneapolis, MN).

Timmermann C, Gerhards R and K?hbauch W (2003). The economic impact of site-specific weed control. Precision Agriculture 4, 249-260.

van Alphen BJ and Stoorvogel JJ (2000). A methodology for precision nitrogen fertilization in high-input farming systems. Precision Agriculture 2, 319-332.

Wang D, Prato T, Qiu Z, Kitchen NR and Sudduth KA (2003). Economic and environmental evaluation of variable rate nitrogen and lime application for claypan soil fields. Precision Agriculture 4, 35-52.

Wang GH, Sun Q, Fu R, Huang XH, Ding XH, Wu J, He YF, Dobermann A and Witt C (2004). In 'Increasing productivity of intensive rice systems through site-specific nutrient management'. (Eds. A. Dobermann, C. Witt and D. Dawe), pp. 243-263. (Science Publishers, Inc., International Rice Research Institute, Enfield, NH and Los Ba?os, Philippines).

Weisz R, White JG, Knox B and Reed L (2003). Long-term variable rate lime and phosphorus application for piedmont no-till field crops. Precision Agriculture 4, 311-330.

Welsh JP, Wood GA, Godwin RJ, Taylor JC, Earl R and Blackmore BS (2003a). Developing strategies for spatially variable nitrogen application in cereals, Part I: winter barley. Biosystems Engineering 84.

Welsh JP, Wood GA, Godwin RJ, Taylor JC, Earl R, Blackmore BS and Knight SM (2003b). Developing strategies for spatially variable nitrogen applications in cereals, Part II: wheat. Biosystems Engineering 84, 495-511.

Whipker LD and Akridge JT (2003). 2003 precision agricultural services dealership survey results. Staff paper no. 3-10. (Purdue University, CropLife Magazine, West Lafayette, IN).

Wibawa WD, Dludlu DL, Swenson LJ, Hopkins DG and Dahnke WC (1993). Variable fertilizer application based on yield goal, soil fertility, and soil map unit. Journal of Production Agriculture 6, 255-261.

Witt C and Dobermann A (2004). In 'Increasing productivity of intensive rice systems through site-specific nutrient management'. (Eds. A. Dobermann, C. Witt and D. Dawe), pp. 359-395. (Science Publishers, Inc., International Rice Research Institute, Enfield, NH and Los Ba?os, Philippines).

Wollenhaupt NC, Mulla DJ and Gotway CA (1997). In 'The state of site-specific management for agriculture'. (Eds. F.J. Pierce and E.J. Sadler), pp. 19-53. (ASA-CSSA-SSSA, Madison, WI).

Wood GA, Welsh JP, Godwin RJ, Taylor JC and Knight SM (2003). Real-time measures of canopy size as a basis for spatially varying nitrogen applications to winter wheat sown at different seed rates. Biosystems Engineering 84.

Yang HS, Dobermann A, Lindquist JL, Walters DT, Arkebauer TJ and Cassman KG (2004). Hybrid-Maize - a maize simulation model that combines two crop modeling approaches. Field Crops Research 87, 131-154.

Yang WH, Peng S, Huang J, Sanico AL, Buresh RJ and Witt C (2003). Using leaf color charts to estimate leaf nitrogen status of rice. Agronomy Journal 95, 212-217.